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SERENDIPITY AS A SOURCE OF EVOLUTIONARY PROGRESS IN SCIENCE

I. Are Scientific Discoveries Analogous to Blind Mutations?

EVOLUTIONARY epistemology (EE) models the evolution of science on the Neo-Darwinian scheme of blind-variation-and-selective-retention.[1] Blind variation in science means that new ideas and theories are generated independently of the problems they eventually solve or of the data they eventually explain. Karl Popper and Donald Campbell relate this requirement to the fact that it is logically impossible to validly infer empirical generalizations or theories from observational data. It is now widely accepted that there is no logic or universal method to arrive at true or successful hypotheses. Furthermore, irrespective of the manner in which a given theory is discovered, there is no logical or analytic method of determining, before testing the theory, whether it is true, or what is the probability that it is true. If, indeed, there is no rational theory-generating method and no analytic way of assessing a theory's validity, there is no *a priori* justification for the theory. This is why Campbell qualifies new scientific ideas or theories as "unjustified variations" (Campbell, 1974a). However, do these "unjustified variations" truly have the same significance as blind mutations or recombinations in biology?

At first sight, the answer to this question would seem to be in the negative, considering that in conceiving new theories, we are already equipped with a guiding apparatus even though this apparatus itself is an evolutionary product. In the present article, we shall indeed discuss the weakness in this somewhat simplistic presentation of the case for evolutionary epistemology; we claim that in "normal" science, the scientist is guided in his conceptual inventions by a certain "wisdom". We then present a different version of EE, in which the "blind" mutations are represented by *serendipity*, a common feature that we consider as fundamental and intrinsic rather than accidental. It is essential to the evolution of "revolutionary" science.

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[1] We refer here to the mainstream version of EE as presented by Popper and Campbell.

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One of the major programs of EE expounds the view that our cognitive apparatus is itself an evolutionary product — both on the organic and on the cultural levels. Our cognitive apparatus determines our ways of concept formation and determines what kinds of predicates will appear in our natural languages, and thus our standards of similarity. We apply a Kantian outlook: we impose our notion of similarity and our regularities upon the world. However, our system of natural kinds and our conceptual systems are not eternal and are not immune to revisions. In science, the system of natural kinds is a product of the selection of ideas and theories. Electrons, which have both particle and wave aspects, are natural kinds in science, although natural languages do not accommodate this kind of predicate. Scientific language is thus the successor of natural language in this respect: it is a product of an extended cognitive apparatus which has evolved with science and which consists of the widely accepted world-view of the scientific community.

Our cognitive apparatus, our general expectations and our system of natural kinds are genetically- and culturally-based. However, they are not infallible and are not rationally justified. Since they are the results of a natural selection process, they reflect both the nature of our species (our interests and needs) and the structure of the environments in which they have evolved. Thus, we are imprisoned within our conceptual system. But, unlike what is claimed by "pessimistic" Kantianism, we transcend this system in the process of scientific evolution.

The system of natural kinds and the related general world picture thus guide us in the construction of a definite hypothesis (among the many logically-possible ones) when explaining a given set of data or when solving a given problem; i.e. they fulfil the task of narrowing down the range of possible explanations or solutions, and in many cases we are left with a unique possibility. Let us look first at an example from everyday life. Suppose we are reading a book and it becomes too dark to read; if there is a lamp in front of us, we do not have to guess blindly in order to generate the hypothesis which will almost always solve our problem. We simply hypothesize that the solution is to switch on the lamp. Although there is no true logical justification for this hypothesis, we do not discover it blindly or generate it randomly. In arriving at our fallible solution, we are guided by our implicit rules of induction and by our system of natural kinds (the latter determines what sort of predicates are amenable to inductive projection). This sort of solution is fallible, but in most cases successful. Thus, although we go beyond what is strictly known (we do not really know what *will* happen when we press the button), and although our hypothesis is logically unjustified, we do not arrive at it blindly; our prior expectations and our general world picture yield algorithms or heuristics which guide us in explaining given data or in solving given problems. It is in this sense that the process of discovery of a solution to a problem would appear to

contradict the analogy with a blind mutation, which is generated independently of its contribution to the survival or the needs of the organism.

Thus, in the development of science, we do indeed have a very elaborate guiding apparatus. "Normal" science, especially, is based on a relatively stable world picture and conceptual system, on established general theories and on methods of theory-construction and concept-formation. Thus, problem-solving in normal science is guided. The prevailing tradition or heuristic partially guides scientists in the choice or in the construction of a hypothesis. For example, in constructing an empirical law scientists are guided either by inductive rules or by statistical methods. Alternatively, there are heuristic principles for the construction of explanatory theories which are sometimes derived from a general metaphysical outlook or world picture. Such is, for example, Émile Meyerson's principle (1908) that theories of material changes, e.g. theories of chemistry, have to be constructed out of conserved "substances", such as atoms and fundamental particles, and conservation laws; the general "recipe" is that whenever some new phenomena do not obey the conservation laws, science has to look for new conserved substances and new conservation laws. In the nineteenth- and twentieth-centuries, theories of the structure of matter were developed more or less according to this principle. It has been shown (Ne'eman, 1966, 1988) that the successful new developments in the physics of particles and fields, for example, also followed this recipe, and that at the foundation of this approach there is a classification. Another example of a ("second order") heuristic principle guiding the evolution of science is that successful scientific explanations in a given field serve as models in constructing further explanatory hypotheses in that field and in other fields (for example, this principle guides us in constructing our present theory). In physics, spontaneous symmetry breakdown was applied to particles and fields, after its success in understanding phase transitions in condensed matter (Goldstone, 1961; Nambu and Jona-Lasinio, 1961; Higgs, 1964). Another example is the idea of quark confinement, which was inspired by the Meissner effect in superconductivity (Nambu, 1976).

Thus, in normal science, even more than in everyday life, the typical case is that scientists appear to solve problems by intentionally trying to solve them, unlike the case of blind mutations, which do not arise as a response to selective environmental pressures. The fact that problem solving in normal science is not blind would therefore seem to contradict the paradigm of natural selection. Campbell, however, in his (1974b) article gives two arguments showing that natural selection still operates in the evolution of science. The first argument maintains, as we mentioned above, that the guiding scientific world picture or tradition is itself a product of preadaptation, i.e. it is a product of selection on the scientific, cultural and organic levels. The range of variation on the scientific level is thereby only reduced by selective processes at the cultural and

organic levels; our cognitive apparatus, which is a product of organic and cultural evolution, reduces the range of possible ideas and theories. The scientific world picture, which is a product of selection on the scientific level, then further reduces the range of possible variation on the level of normal science. We observe, therefore, the following rule in this hierarchy: the range of possible variation at any given level is reduced by selective processes at the underlying level (see Amundsen, 1989). Thus, normal science is preadapted by the process of selection to its domain of investigation.

If we look for the parallel situation on the organic level, we notice that the range of possible variation is limited by the constitution of the organism's genotype and by the laws of molecular biology. More specifically, the range of mutations which a given gene can undergo is restricted by the gene's structure. Hence the mutational repertoire of a gene pool is restricted or determined by the evolutionary history of the species, just as the repertoire of new ideas in science is restricted by tradition or by the world picture. Furthermore, as was argued by Francisco Ayala (Dobzhansky *et al.*, 1977, pp. 65–66), when a species is in a state of stability (which is the parallel of normal science), and when the environmental conditions are stable and the species does not move into a new habitat, it is more probable that new mutations will be detrimental rather than advantageous. The reason for this is that if a certain variation does not appear with a high percentage in the gene pool, it is most probable that it has been tried in the phylogenetic history of the species and has already been repressed. Only radical environmental changes might still expose an advantageous variation. The parallel statement with respect to science is that radically new ideas are repressed in a mature, or an established, stage of normal science; when unexpected experimental data are not produced, no radically new experimental technology is introduced and no new theoretical results are imported from other areas. Thus, the presence of a restricting and guiding tradition does not contradict the model of natural selection.

Campbell's second and main argument, in defending natural selection in science, is that even in the presence of a tradition and a background knowledge there still *must* remain an element of blindness in scientific problem-solving, since the tradition or heuristic and the background knowledge do not *uniquely* determine the solution for a given scientific problem. Thus, Campbell maintains that, in general, there remains a range of possible solutions among which the scientist can only choose blindly, i.e. independently of the data or of the problem to be solved. His argument is analytical or logical: "In going beyond what is already known, one cannot but go blindly. If one can go wisely, this indicates already achieved wisdom of some general sort . . . which limits the range of trials" (*ibid.*, p. 422). Note that to "go wisely" still means here to go blindly, though within a narrower range of trials. This brings us back to the logical argument mentioned at the outset. Here the argument applies to the

situation where we are equipped with a guiding apparatus and background knowledge. Indeed, logical inference is content-preserving so that *logically* we cannot justify any piece of knowledge which exceeds the information contained in the premises, including the information carried by the guiding apparatus, namely our genetically- and culturally-inherited wisdom.

However, in contrast with the above argument, in many cases scientists do arrive at new pieces of knowledge, including new laws and theories, in a non-blind manner. There are two major ways of doing this: by deductive inference and mathematical derivation, or through experimentation and observation. In normal science, scientists aspire to gain new knowledge or to solve problems in a methodical manner through these means. Thus blind search is by no means typical to normal science; it is the exception rather than the rule.

The scientist may derive a new theoretical result or prediction from an established theory. For example, Maxwell derived the existence of radio waves from his equations. However, although the results of a deductive inference or a mathematical derivation are logically contained in the premises, it is not always true that the results are known to the scientist before he makes the derivaton or the inference. Thus, it is not true that Maxwell "knew" about radio waves as soon as he arrived at his equations. According to the conception of knowledge we employ here, knowledge is not deductively closed. If it were so, we would have to attribute to every child the knowledge of all the theorems of Euclidean geometry as soon as he learns the axioms. However, deduction and mathematical derivation are by no means blind activities. Thus, *deduction is the prototypical way of gaining new knowledge in a non-blind manner*.

Deductive inference is not confined to deriving theoretical predictions from a given theory. The most common way of gaining new knowledge by deduction or by mathematical calculation is when scientists derive a prediction from a law or a theory in conjunction with statements describing observational data or initial conditions. Thus, if the data or the initial conditions are accepted by the scientific community as true or reliable and if the theory is highly established, then the prediction may constitute a new piece of knowledge. In any case, the prediction can be tested experimentally and if the results agree with the prediction, we must conclude that we have here a new piece of knowledge which was gained non-blindly, since the prediction guided us in deciding where to look. In this manner scientists predict not only singular events such as an eclipse but also empirical laws such as the laws which govern the behavior of a given configuration of bodies (e.g. a planetary system) or particles (e.g. an atom of a given element or a nuclear system), which can be derived from Newtonian mechanics or quantum mechanics, respectively, in conjunction with the physical properties of the system.

However, there is a wider range of scientific activity which is modeled on

deductive inference and which is therefore non-blind. It includes research programs (e.g. Lakatos, 1970) or processes of problem-solving which are guided by some comprehensive heuristic. We may view these processes as "generalized" inferences, as if the heuristic fills the gaps in the deductive inference, playing the role of an "inference-license" or of a missing premise. The accepted heuristic for problem-solving and for theory-construction in a given field is derived from the guiding apparatus of the scientific community. The heuristic narrows the range of possible explanations or solutions so that it may reduce scientific inference to a deductive inference. The example of the discovery of the planet Neptune is instructive. The anomalies in the motion of Uranus in view of Newtonian theory were explained by Adam and Leverrier by assuming the existence of an unknown planet, Neptune, perturbing Uranus' motion, besides the perturbations caused by Saturn. The assumption about the existence of a perturbing planet was guided by the general heuristic that the motion of a planet is only affected by gravitational forces due to the sun and other planets. This heuristic was not directly derived from Newtonian theory but was tacitly assumed. No one thought about other possibilities, such as the possible existence of other forces affecting planetary motion besides gravitation, or a change in the law of gravitational force; the law of force was part of the theoretical "hard core". The theoretical hard core and the guiding heuristic did not have any logical validity but they were parts of the paradigm or the guiding apparatus at that time. Indeed, Leverrier himself similarly postulated the existence of another planet, Vulcan, in order to explain the abnormal behavior of Mercury. Vulcan has never been found. Instead, it was a change in the law of force, namely Einstein's general theory of relativity, that solved the problem, breaking out of the above paradigm. Thus, the problem regarding Uranus' motion was solved by calculating the position of Neptune on the basis of Newtonian theory and the available astronomical data. Although the mathematical solution involved some guessing, Adam and Leverrier arrived independently at the same result. This is, therefore, a typical case of a non-blind discovery; the solution of the problem of Uranus' abnormal behavior was obtained as a result of an activity which aimed at solving that problem. A similar situation developed in particle physics when the J/Psi particle was discovered in 1974. It was immediately explained by the postulation of a fourth type of quark, the "charmed" one. This would also explain the non-existence of strangeness-changing weak currents (the "GIM mechanism"). The hypothesis was confirmed by the discovery of the D mesons, analogous to K mesons, but with the strange quark replaced by a charmed one.

The second way of generating new variations in science in a guided manner is by inductive generalizations or by statistical inference from observed data. In this manner empirical generalizations and laws of nature are derived from observation and experiment without a resort to blind groping. The available

conceptual system and the general world picture narrow down the range of variation such that in a given situation controlled experiments may lead to a unique generalization. Furthermore, if there is a comprehensive theoretical framework and elaborate methods or heuristics for theory-generation (such as the Meyersonian heuristic), new models or theories may be deduced from experimental results. In such a case the number of possible solutions of a given problem or the number of possible explanatory theories may be manageable. In order to obtain a solution the scientist will conduct controlled experiments which may leave him with a unique solution, eliminating all other alternatives. We may take Rutherford's discovery of the atomic nucleus as an illustration. The accumulating experimental results at that time indicated that the atom is made of a positive charge and of negatively charged electrons (it was part of the world picture that matter is composed of atoms). The question was: how is the positively charged matter distributed within the atom? Room was left for a few logical possibilities only. One possible answer was that there is a continuous ball of positive charge (J. J. Thomson's "plum pudding" model). A second logical possibility was that the positive charge is concentrated in one or more particles, leaving empty space within the atom. Rutherford probed the structure, using alpha-particles. He found that a small percentage of the scattered particles were reflected back from the film. By mathematical analysis Rutherford came to the conclusion that the positive charge must be concentrated in a small nucleus. Reconstructing the whole process, we must conclude that the final result involved no blind groping. The general picture of the structure of matter and the accumulated data led inevitably to that result; we might say that Rutherford learned it from his experiments.

Thus, the general world picture and the heuristic may narrow down the range of possible variation so that the arrival at the final discovery is a result of accumulated experimental data and deductive inference or mathematical derivation. This is the reason why scientists often claim that they deduced or derived a certain theory or model from the data. This deduction or derivation is valid only in view of the accepted wisdom of the scientific community. Also, in this light we can understand how scientists who share a general theoretical framework, general beliefs and heuristics do arrive at a consensus with respect to the acceptance of a certain theory, or sometimes independently arrive at the same theoretical result, as if it were a result of a straightforward mathematical calculation.

True, the above description refers to the ideal case of scientific inference which is not always realized in practice. In many cases an element of chance infiltrates into the process, since the available heuristic and world picture, which have evolved with past experience, cannot always meet a new challenge. Therefore the guiding wisdom does not remain frozen even in normal science. It undergoes small changes following the ongoing experience of problem-

solving. Our main point, however, is that, in principle, blindness is not a necessary condition for gaining new knowledge and for generating new solutions to problems or new explanatory theories. On the contrary, in normal science scientists expect to solve problems and to discover explanatory theories by inference or by heuristic-guide problem-solving. Thus the model of blind variation would appear to fail when we refer to normal science, which does not break with tradition; if scientists adhered to this model they would not waste so much time and energy in trying to solve problems in a methodical or a guided manner. It is only radical or "revolutionary" changes in science that can clearly be described as typically, and in certain cases (as we will see in the next section) necessarily, involving blind variation. However, even scientific revolutions have their roots in normal research, i.e. in a guided activity.

And yet, as we will show in the next section by studying the nature of the research process, the paradigm of natural selection can indeed be retained over a very wide range. We will suggest that science advances via a special class of blind discoveries, even though these originate in the intentional or guided action of problem-solving. Although scientists do employ methods and heuristics which guide their research in view of the data, these methods and heuristics frequently lead them to unexpected discoveries. Furthermore, we will see that the "mechanism" which turns a problem-guided activity in an unforeseen direction may also be responsible for the "revolutionary" discoveries which destroy the prevailing order and open new vistas for science.

II. Serendipity-driven Advance of Science

In *The Sleepwalkers* (1964), Arthur Koestler writes: "... the manner in which some of the most important individual discoveries were arrived at reminds one more of a sleepwalker's performance than an electronic brain's." Our thesis provides a specific interpretation for these words. We would like to suggest that radical scientific changes are very often triggered unintentionally by an innocent problem-solving activity within normal science. At times an activity intended to solve a given problem leads to unintended results. This pattern of discovery might still keep us within normal science. However, it might initiate a process of scientific revolution. In fact, blind discovery is a necessary condition for scientific revolution; since the scientist is in general "imprisoned" within the prevailing paradigm or world picture, he would not intentionally try to go beyond the boundaries of what is considered true or plausible. And even if he is aware of the limitations of the scientific world picture and desires to transcend it, he does not have a clue how to do it; he is blind to any territory which lies outside the one governed by his world picture. Here Campbell's argument applies: in going beyond the prevailing world

picture, one cannot but go blindly. In the previous section we mentioned two ways of gaining new knowledge in a non-blind manner and both ways will always keep us within the confines of our framework of knowledge. By deduction we cannot construct a radically new conceptual system or world view. Also, the heuristic which helps us in constructing theories in view of the observational data is part and parcel of our world picture and thus it cannot guide us in transcending the world picture.

Thus, one of the major ways of transcending an established state of knowledge is to do it unintentionally while trying to solve some problem within the confines of the prevailing paradigm. Indeed, it is well known to working scientists that a large percentage of research programs in natural science deviate from the original path planned for them, as if chance "drags" the research program in a new direction, a direction which sometimes leads to the discovery of a new phenomenon or a new domain of reality. This is how serendipity is realized in natural science (see Ne'eman, 1980).

The term "serendipity" was coined by Horace Walpole. In a letter written to Horace Mann in January 1754 he says that he formed this term following his reading of a "silly fairy tale" called "The Three Princes of Serendip" (Serendip is an ancient name for Ceylon or Sri Lanka). The three heroes of this tale "were always making discoveries by accidents and sagacity, of things they were not in quest of" (Lewis, 1960). The Oxford English Dictionary defines the term as "the faculty of making happy and unexpected discoveries by accident". The Dictionary adds, however, the following sharper definition: "looking for one thing and finding another". The latter definition refers to cases where one looks for A and finds B. Thus the scientist may act in a guided manner in order to solve a problem — while he discovers that the end result provides a solution for another problem, of which he was not aware. The notion of serendipity implies that the discoverer is aware of the fact that he found B, or at least of the fact that he found something unexpected or significant. Thus, science can benefit from a hint given by Nature only if there are open-minded scientists who grasp the significance of the hint. Sometimes the scientist who made the discovery is not aware of the full significance of his discovery while other scientists complete the task. So in many cases serendipity in science is a collective enterprise.

One of the best known cases of that nature is Fleming's discovery of penicillin. Taking a Petri dish containing a bacterial culture he noticed that the loose cover had not been properly set, and a mold had grown over the exposed area. The bacteria, on the other hand, were dead. This may have occurred to other researchers before him and their conclusion must have been to see that lids should be properly clamped... Fleming realized that this implied that some molds could kill the bacteria.

A very similar sequence ushered the presently popular "superstring" hypo-

thesis (see for example Schwarz, 1985) in physics. "Dual Models", later shown to represent the quantum excitations of a string, were developed in order to explain the strong nuclear force. One difficulty that appeared to plague the model was the appearance of a spin-two massless state as the lowest physical state of the string's spectrum of excitations. Strong interactions involve only massive states, and physicists tried unsuccessfully to give a mass to this spin-two state. Yoneya (1974) and Scherck and Schwarz (1974) suggested that the quantum string be reinterpreted as a theory of quantum gravity (since gravity is mediated by gravitons, massless spin-two "particles") rather than of the strong nuclear interaction. The string tension, the only free parameter in the theory, thus had to be changed by twenty orders of magnitude! Thus a theoretical construct invented to explain the strong nuclear force led to a deeper understanding of quantum gravity.

Our main claim is that serendipity in science is not a casual phenomenon. Understanding the role of serendipitous discoveries will contribute to understanding the epistemic role of science and its evolutionary character. Serendipity supplies science with its blind edge. The human mind makes plans which have a chance of yielding successful results only in familiar territories of Nature, while serendipity causes science to deviate from its planned course towards unexplored domains of Nature. Actually, serendipity enables the human mind to transcend established frameworks of knowledge, established world pictures.

The requirement of blind discovery is realized in the phenomenon of serendipity in such a way that it does not contradict the fact that scientists do act intentionally and that they direct their efforts towards solving given problems. Indeed, when a scientist makes a serendipitous discovery he does not guess blindly. Rather he is occupied with directed problem-solving in the framework of a research program, employing algorithms and established methods. However, since he tries to solve problem A, being aware of problem A, while accidentally solving (another) problem B, the solution of problem B is, indeed, generated blindly with respect to B. Thus, the discoverer does act intentionally, being affected by the problem he intended to solve; and yet he ends up making a "blind" discovery. By this we reconcile in a straightforward manner the fact that science appears to be a guided enterprise with the evolutionary model of blind variation. Thus, variations are generated via the activity of problem-solving and are selected by problems which they were not intended to solve. We might describe the situation by saying that in his problem-solving activity the scientist generates "solutions in search of problems".

Now, the more profound question is why does science advance in this manner? Why, for example, shouldn't scientists who wish to find novel solutions to problems (or to free themselves from the prevailing world picture

and look for a new one) adopt the Feyerabendian slogan "anything goes" and start gambling with Nature? Why should they necessarily expect to find unexpected clues for the understanding of natural phenomena while conducting "normal" research? Why shouldn't they instead draw their inspiration, for example, from works of art, fairy tales or wizards? The answer to this question may rest on the stepwise pattern of the growth of science. When one plays with existing building blocks one may discover a new combination or a new configuration which constitutes a solution to a problem. Perhaps every new tool is discovered in this way; the chimpanzee, for example, may discover by innocent playing with sticks that two sticks can be combined to form a new tool which can be used to knock down a banana from a tree. The scientist playing with theoretical concepts while trying to solve a problem may find a new theoretical construct with which he can solve another problem. A novel form may appear as an emergent property out of familiar constituents.

What is characteristic of the above pattern of discovery is that the discovered entity is constructed out of existing building blocks. There can be no shortcuts in this process. A building cannot be constructed directly out of protons, neutrons and electrons or even out of chemical compounds. First the bricks must be prepared. However, in our context the most appropriate analogue can be drawn from organic evolution: mutations and recombinations are superimposed on given genes and on given genetic structures. Following a process of natural selection, the system may stabilize with a new genetic structure or a new gene pool. Thus the new state of stability emerges out of the old one. For example, *Homo sapiens* arose from some hominid ancestor. It could not have evolved directly from a unicellular species, for example. (This is, in fact, why the statistical arguments used to refute evolution were wrong. The probability of man forming through a long sequence of tiny evolutionary steps is much greater than that of his spontaneous emergence from a chance rearrangement of his 10^{28} atoms.) Similarly, a new stratum of knowledge can be constructed out of the prevailing stratum. The new conceptual system or the new world picture is constructed on the basis of some central concepts and ideas of the old world picture. Thus, quantum mechanics employs "mutated" concepts of classical mechanics such as energy, momentum and the Hamiltonian formalism. It is improbable that quantum mechanics would have been created on the basis of Aristotelian physics or even on the basis of the early version of Newtonian physics, before classical mechanics was fully developed by Euler, d'Alembert, Lagrange and Hamilton into a general dynamical theory. Thus, before a new layer of reality is exposed, and a new stage of knowledge is made to emerge, the prevailing layer should be thoroughly explored and the prevailing stage should be fully developed.

Hence, discovery by serendipity is essential for the continuity of the advance of science. This claim depends on the assumption that variations at the organic

and at the scientific levels are not generated *in vacuo*, out of nothing; they are imposed on existing forms — existing genes or existing ideas — respectively. Thus, serendipitous discovery guarantees both independence in terms of problem-solving pressures (blindness), and continuity.

It should be stressed that serendipity is needed for the advance of science because we conduct our scientific investigations from within a given framework: a given conceptual system or a given world picture. Had we adopted the naive empiricist view that we can acquire objective knowledge about the world just by making unbiased observations, then serendipity would be unnecessary. Serendipity is needed in order to transcend an established framework of knowledge.

III. Implications for the Philosophy of Science

It is evident from the above discussion that the principle of discovery by serendipity is both descriptive and normative. It is descriptive since we claim that science in fact advances by serendipitous steps. To be more precise, our approach is explanatory rather than merely descriptive; we start with an evolutionary theory of science which, on the one hand, is checked against historical evidence and which, on the other hand, attempts to explain scientists' decisions and acts. Our approach is normative, since it maintains that in view of the basic assumptions of our theory, science can make significant progress only by serendipity. Hence we may treat our theory as part of an explanatory philosophy of science which has both explanatory and prescriptive implications (see Kantorovich, 1988). Our theory explains, for example, the fact that scientists prefer theories which yield unexpected predictions. It also may add to our understanding of two phenomena which characterize modern science — mathematization and cooperation.

(a) *Predictability and epistemic profit*

The principle of discovery by serendipity sheds light on one of the most important methodological requirements of a scientific theory, i.e. that a theory, besides explaining known phenomena, should generate successful predictions of unexpected events or phenomena. Thus, for example, Maxwell's electromagnetic theory unexpectedly explained the phenomenon of light, and in addition predicted the existence of radio waves, establishing relations between optical and electromagnetic phenomena. This requirement cannot be accounted for by logic alone. We could perhaps be satisfied by "relegating" it to the psychological arena; yielding an unexpected prediction has a dramatic effect, like telling the future or performing magic, thus persuading scientists to accept the theory. However, in view of our principle of serendipity we can avoid this sort of

psychologism. If a theory which was constructed in order to explain A also predicts B, it means that we explain B unintentionally, i.e. by serendipity. Namely, in constructing the theory, the scientist could not be influenced by B, i.e. he was blind to B. Thus, Maxwell did not set out to explain light; he calculated the velocity of propagation of electromagnetic waves and was surprised to find that it fitted the known value of the velocity of light. When Dirac constructed his electron theory, he intended to describe and explain properties of the electron as a quantum-mechanical particle under relativistic conditions. The prediction of the existence of the positron came as an unexpected by-product. A new "world", the world of antiparticles, was thus discovered, with the relevant particle–antiparticle symmetry. Of course, after the positron was detected, its existence and its properties became parts of the theory's explanandum. Thus when we require high predictive power, it means that we require that the process of discovery of the theory will be as blind as possible to the phenomena the theory eventually explains. The methodological statement that a theory is confirmed by its successful predictions can be translated into our evolutionary language by saying that the theory is selected by facts and phenomena which were not taken into account in constructing the theory.

The ideal case would be when the discoverer generates the theory independently of any factual knowledge. The discovery would then be totally blind to any data and if the theory yields successful predictions, then the "epistemic profit" will be maximized. The epistemic profit can be defined as the ratio of the amount of factual knowledge (or information) predicted and explained by the theory to the amount of factual knowledge invested in constructing the theory (in practice, of course, there is no simple measure for these "quantities" but in many cases scientists can estimate the ratio). In Dirac's case, the input was just Lorentz-invariance, the output a doubling of the entire particle world. Tautologically, the profit is maximal in a revolutionary change, following a blind theoretical leap. Of course, falsifiability is thereby also maximized.

In view of our principle, we can also explain the negative methodological attitude towards *ad hoc* modifications imposed on a theory in order to explain some empirical data if they do not yield new predictions. Ptolemaic astronomy, for example, which explained away every discrepancy between the theory and the facts by employing epicycles, yielded no epistemic profit. Such *ad hoc* modifications are totally guided by the data, whereas our principle demands that the generation of new variations be blind to some of the data they explain.

Classifications, such as Linneus' tabulation of the living kingdom, Mendeleev's chart of chemical elements, or the SU(3) symmetry of nuclear particles, are interesting when they predict new species — so as to be falsifiable. However, they then also take on a characteristic of "classifying A and finding B", with B's emergence representing a broadening of the known universe. Even

if we know from experience that new species may exist, we do not know what they are without the classifying theory.

A straightforward case of serendipity occurs when the theory yields an unexpected explanation for a known phenomenon or an unexpected solution for a known problem. For example, as we mentioned above Maxwell's theory explained light, Newton's theory of gravitation explained the phenomenon of tides and Einstein's general theory of relativity solved the problem of the abnormal behavior of Mercury. Thus, one of the major cases of advance occurs when a new scientific theory solves a known problem which it was not intended to solve. The discoverer in this situation solves the problem by using a theory which was constructed or discovered by scientists who were not aware of the problem.

Thus, serendipitous events can be divided into two main classes:

(1) intending to solve (explain) A, but solving (explaining) B instead;
(2) intending to solve (explain) A, and solving (explaining) B in addition to A.

The case of an unexpected prediction belongs to class (2). Class (2) also includes cases where a research program which solved the original problem A continues to evolve and solves problems, explains phenomena or leads to ideas which were not dreamt of at the start. Ernest Rutherford, for example, was not satisfied with the idea of light quanta, since he thought it lacked a physical basis, yet the Bohr–Rutherford model, which developed from his initial model of the atom, was based on this very idea and lent it a high degree of confirmation. In general, a research program starts with an initial version of a theory and ends up with a different version due to *ad hoc* corrections and modifications made in the course of the development of the research program. Thus the later version can be seen as an outcome of the initial version, the initial discovery. The initial version is intended to solve a given problem, whereas the subsequent versions of a progressive research program (Lakatos, 1970) solve additional problems. Thus, when we demand high predictive power we refer not only to a given theory as it stands, but to its potentialities which can become actualized in a dynamic process of modifications and improvements (see Kantorovich, 1979).

Genes or gene combinations, too, undergo "*ad hoc*" changes. If we look at the manner in which organs actually evolve, we can see that an evolutionary line does not seem to be a preplanned process. Rather that reflecting a program or a purpose, the structure of an organism reflects the past, namely, the history of the evolutionary line. If the evolutionary line starts with a certain structure, imperfectly adapted to a certain niche, all future adaptations to changing environmental conditions will be "*ad hoc*" modifications imposed on the initial structure. Thus organs undergo changes which make them capable of performing new functions. For example, jaws were developed in fish from

gill arches, and legs developed from fin supports — to serve perhaps for locomotion in very shallow water. *Homo sapiens*' hands, which paved the way to human culture, evolved from forelimbs of a predecessor species, which served perhaps mainly for climbing trees. Of course, not every structure is amenable to every *ad hoc* modification, and if the latter is successful, it is due to the potentialities inherent in the original structure.

(b) *Mathematization and socialization*

There are two characteristics of modern science which make it liable to serendipitous developments: the complex deductive or mathematical structure of scientific theories and the highly cooperative nature of scientific research. Although these two phenomena seem to take place on totally different levels — cognitive and social — they can be viewed as serving a common purpose. As we have already mentioned, complex mathematical theory may yield far-reaching predictions of which the scientist proposing the theory cannot be aware at the outset. Similarly, a scientist proposing a theory cannot know in advance how the theory will be interpreted or exploited by other scientists and in what direction the theory will be developed and modified by his collaborators or by his successors; after a theory or an idea appears in the public arena it has a life of its own and does not remain any more under the control of its originator (see again Rutherford's case). Thus, the discoverer of a new idea or theory is blind to some of its far-reaching consequences, which are obtained either by mathematical development or as a result of its processing by the scientific community. He may, therefore, unintentionally trigger a process which leads to a solution of a problem of which he was not aware. The principle of serendipity, therefore, also sheds some light on the epistemic function of the mathematical nature of modern science and of the cooperative nature of modern scientific research.

IV. Landmarks of Serendipity in Physics

In this section we will describe two of the greatest revolutions in physics in the light of the principle of serendipity.

(a) *Kepler: the conscious sleepwalker*

Johann Kepler is one of the heroes of Koestler's *Sleepwalkers*. Kelper's original problem was to explain why there are exactly six planets and why the distances between their orbits are as they are. He was impressed by the Pythagorean view that the world is governed by mathematical relations and hoped at first to find the solution to his problem in the realm of arithmetics. He

then looked for the solution in plane geometry. After he failed there too, he turned to solid geometry. The erroneous number of planets, six, gave him the clue for his model of five Platonic solids (the five regular convex polyhedra) on which he erected the universe. He associated the five perfect solids with the five interplanetary regions and tried to find out how the proportions between the five solids are related to the distances between the orbits. After many unsuccessful attempts to explain away the discrepancies between his model and the observational data, he turned to another Pythagorean model: he tried to construct the heavenly motions as "a continuous song for several voices (perceived by the intellect, not by the ear)". His model of the universe was thus constructed out of the five Platonic solids and the musical harmonies of the Pythagorean scale. In his attempts to improve his model he needed exact figures of the eccentricities and mean distances. These were supplied by Tycho Brahe. However, Kepler encountered new problems in Tycho's data and found other parameters to investigate, instead of the relative distances of the planets. The attempts to solve the new problems eventually led him to the discovery of his three Laws.

The processes by which he arrived at his Laws involved many sequences of trials and errors. His Pythagorean models stayed in the background and set the framework for his investigations. However, when he struggled with the data, he arrived at his successful solutions mostly by error or by chance, not always recognizing their value or significance. His struggle with the Martian orbit led to the First Law. His first assumption was naturally that Mars' orbit is circular. Then he hypothesized an egg-shaped orbit. After abandoning the egg-hypothesis, he constructed the Martian orbit by very precise calculations and obtained a circle flattened at two opposite sides. He then found by chance that a simple relation holds between two quantities related to the geometrical form of the orbit. As a result, he obtained a simple formula expressing the functional relation between the planet's distance from the sun and its position (Koestler, pp. 336–338). Since analytical geometry was not available in his time, he did not realize that the formula characterizes an ellipse. And yet in his next step, he conjectured that the orbit is an ellipse. He thus discovered his First Law twice: once by chance and once by making a hypothesis and testing it. This hypothesis was almost the only one left for him after he had eliminated all other alternatives. The belief in circular orbits was so deeply entrenched that Kepler could depart from it only by chance or by a lengthy process of trial and error.

The process by which Kepler arrived at the Second Law was hazardous in a different way. He discovered that the radius vector of the earth's orbit sweeps out equal areas in equal times, after making three erroneous assumptions which somehow led to the correct result. The assumptions were the following: "(a) that the planet's velocity varies in reverse ratio with its distance from the sun; (b) the circular orbit; (c) that the sum of eccentric radii vectors equals the area." (*ibid.*, p. 591). With respect to assumption (b), note that he discovered the Second Law first. This process of "error begetting truth" (to use Koestler's expression), which is characteristic of Kepler's investigations, amounts again to blind discovery. Indeed, if we start a deductive inference from false assumptions there are equal chances to get a true and a false conclusion and the inference is thus reduced to gambling.

The discovery of the Third Law came about after many years of search for a correlation between a planet's period and its distance. Kepler arrived at the Law after innumerable trials. Hence chance did not play a significant role in the final discovery.

In general, Kepler did not realize the importance of his Laws. Without Newton's theory the Laws looked arbitrary. The belief in circular orbits of heavenly bodies was deeply rooted in the Ptolemaic and the Copernican world picture and Kepler could see no reason why the planets should move in ellipses. He therefore treated the First Law as a necessary evil. The Second Law was treated by him as a computational device. The Third Law was treated just as one more step in the construction of Celestial Harmonies. Kepler thus thought that he was constructing his Pythagorean models, the three Laws being just building blocks in this process. He was partially imprisoned within the old traditions of Neoplatonism and Pythagoreanism. He could not therefore realize that he had made a decisive step in transcending this "paradigm".

In sum, Kepler started with a problem in the old "paradigm", trying to give mathematical sense to the number of planets and to their spatial distribution. He ended up identifying the mathematical regularities of planetary motion, a discovery which led eventually to Newtonian Mechanics and to a new paradigm. The framework of Kepler's grand research program was set while Kepler was totally blind to the final data and to the final problem which he eventually solved. Although Kepler's original model of the solar system has left no remnant in physics, the mathematical element of his Pythagorean outlook did become part of the world picture of physics, established by the Newtonian paradigm.

We can trace Kepler's train of reasoning from his writings. Other great scientists, such as Copernicus, Galileo and Newton, mainly give us the final results of their investigations, hence we cannot trace serendipitous elements in their work. Moreover, Kepler is partly aware of the serendipitous nature of his discoveries. He writes in the Preface to his *Astronomia Nova:* "What matters to me is not merely to impart to the reader what I have to say, but above all to convey to him the reasons, subterfuges, and lucky hazards which led me to my discoveries. When Christopher Columbus, Magelhaen, and the Portuguese relate how they went astray on their journeys, we not only forgive them, but would regret to miss their narration because without it the whole, grand entertainment would be lost. Hence, I shall not be blamed if, prompted by the

same affection for the reader, I follow the same methods." (Cited in Koestler, *The Sleepwalkers*, p. 318.) Indeed, if the notion of "serendipity" were available to Kepler he would have used it, since Columbus' story is one of the most prominent examples of serendipity in human history. It seems, therefore, that Kepler felt that the zigzag path of his investigations is significant enough to deserve a description in his scientific writings.

(b) *Planck: the reluctant revolutionist*

Of the two revolutions which shook human thought at the beginning of the twentieth century the quantum revolution seems to be the more radical. Relativity theory was based on classical theories, whereas the idea of energy quantization and the subsequent principles of quantum mechanics sharply depart from classical physics. (Indeed, nowadays relativity theory is included in textbooks as part of classical physics.) It is suggestive, therefore, that the quantum revolution arose as a result of a serendipitous discovery, whereas the special theory of relativity emerged out of a systematic analysis of known concepts and theories. And yet even in this case, a new theory of space and time (B) arose out of measurements that were meant to measure the velocity of the earth through the ether (A).

Planck attempted to solve a problem concerning the Second Law of Thermodynamics and ended up solving the problem of black-body radiation. The implications of the discovery had a radical impact on the whole world picture of science. Planck treated the Second Law as an absolutely valid principle. Hence he did not accept Boltzmann's statistical approach, which treated the increase in entropy, asserted by the Second Law, as "highly probable" rather than absolutely valid. Planck spent many years trying to clarify and understand deeply the Second Law. Before the turn of the nineteenth century he consequently became interested in the problem of black-body radiation.

The problem of electromagnetic radiation emitted from a very small cavity in a hot furnace had occupied physicists for half a century. The discrepancy between the observed distribution of intensity of the emitted light for different wavelengths and the predictions of classical physics was termed "the ultra-violet catastrophe". The curve based on the experimental data showed a very weak intensity for short wavelengths, in the ultra-violet region. The intensity increased with wavelength until it reached a maximum at a certain wavelength (which corresponded to the dominant color of the light emitted from the furnace) and then decreased and again became very weak in the infra-red region.

The theory of black-body radiation was developed by Rayleigh, Jeans, Kirchhoff and Wien on the basis of classical theories: the electromagnetic theory for treating light radiation and Newtonian mechanics for treating the oscillating electrons within the walls of the furnace, which absorb or emit the

light. Since the electrons in the walls must be at equilibrium, they have to emit and absorb on the whole the same amount of radiation energy. Hence, a third theory — Boltzmann's statistical mechanics — was incorporated in order to calculate the energy distribution in a state of equilibrium. Only in the infra-red region was the curve of the energy distribution (or the intensity of the emitted light at equilibrium) predicted by these theories indeed similar to the experimental curve. In the ultra-violet region, the intensity increased indefinitely with decreasing wavelengths. Thus, at least one of the three theories employed for the calculation must have been wrong.

As mentioned above, Planck's motivation in attacking this problem stemmed from his interest in the Second Law. He had studied problems related to the scattering of electromagnetic waves by an oscillating dipole, which had direct implications for the scattering of light by the furnace's electrons. His aim was to understand how the radiation within the furnace is kept in a state of equilibrium at constant temperature. He was thus engaged in the thermodynamics of radiation. In the course of his investigations he planned to derive the Second Law for a system consisting of radiation and charged oscillators, in an enclosure with reflecting walls. We will not describe here the details of these investigations with all their technicalities. We would rather refer the interested reader to Martin Klein's detailed historical article on this subject (Klein, 1966). We will only cite a few statements describing the aim of Planck's research program. Klein writes: "The ultimate goal of this program would be the explanation of irreversibility for conservative systems and, as a valuable by-product, the determination of the spectral distribution of black-body radiation." In doing this, Planck hoped to "put an end, once and for all, to claims that the Second Law was merely a matter of probability. How was Planck to know that he was headed in a very different direction, that he had started on what he would later call 'the long and multiply twisted path' to the quantum theory?" It is interesting to note that, in describing Kepler's thought, Koestler speaks about the "zigzag course of his reasoning". This seems a paraphrase on the above-cited words of Planck, taken from his Nobel address. Needless to say, Planck did not succeed in attaining his original goal (just as Kepler did not) and the by-product turned out to be the major result of his enterprise.

In the last stage of his long serendipitous path he found that the problem of black-body radiation would be solved if the energy of an oscillator could take only values 0, E_0, $2E_0$, $3E_0$ . . ., where $E_0 = hf$, f being the frequency of the oscillations and h a constant to be determined by experiment. Boltzmann had already used this idea as a computational device, going to the limit $E_0 \to 0$. After six years of unsuccessful attempts to solve the problem, Planck decided to employ E_0 without going to the limit. Planck explains this move as "an act of desperation" and he treats it, as he says, as "a purely formal assumption, and I did not give it much thought except for this: that I had to obtain a

positive result, under any circumstances and at whatever cost." Thus, Planck's discovery was doubly serendipitous. First, his original goal was related to the Second Law of Thermodynamics but he ended up solving the "ultra-violet catastrophe". Second, when he arrived at the solution of the latter problem, he employed it reluctantly, without realizing at first its far-reaching implications. He treated the energy quantization as a computational device rather than as a law of Nature. He did not commit himself to the existence of quanta as real physical entities.[2] This may remind us of the instrumentalist spirit of Osiander's preface to Copernicus' *De Revolutionibus*, in which Osiander explains that Copernicus meant his heliocentric hypothesis to be just a computational device, or Kepler's treatment of his second Law. When Planck used his computational subterfuge, he did not dream that it would have immediate implications in explaining phenomena such as the photoelectric effect and atomic spectra, not to mention the subsequent developments and successes of quantum physics. Einstein was first to treat quanta seriously, in explaining the photoelectric effect in 1905.

V. Serendipitous Discovery of Natural Phenomena

There is a different kind of serendipitous discovery which also contributes as an evolutionary process to the advancement of science, but does not seem to be analogous to blind variation. We are referring to the discovery of an unexpected phenomenon such as that of X-rays and radioactivity. As we shall see in the following examples, the original aim, of the investigation and the final result in these cases were entirely different — researching A and discovering B. The final result, however, was not a solution of a problem but the emergence of a new problem awaiting a solution. The discovery of an unexpected phenomenon in the course of normal-science research is similar to a new environmental pressure exposed by the species' activity (such as a migration or an activity which undermines the ecological balance in the natural habitat). The new environmental conditions pose a challenge to the species, which has to overcome new dangers and difficulties or exploit new opportunities. There are three possible sources of variation which might enable the species to meet the challenge:

(a) Preexisting genes which are responsible for other functions. For example, in certain insects genes which are responsible for metabolic functions also confer resistance to insecticides (in this example, the new environmental condition came about as an indirect result of the species' activity).

[2] One of the present authors (Y. N.) tended to regard his "fundamental field with baryonic charge 1/3" (Ne'eman, 1963, 1987) as a computational device in the beginning. They are now known as "quarks" and regarded as the basic bricks of nuclear matter (see Pickering, 1984, p. 116, note 90).

(b) Genes which undergo "*ad hoc*" modifications (see section 3a).

(c) Genes which have been kept in a dormant state, or genes with low frequency in the population, are activated by the new environmental conditions and spread through the population, since they endow high survival value. This is typical of the evolution of resistant strains of bacteria.

Similarly, novel phenomena may be explained by an existing idea or theory which was generated in order to explain other phenomena, by a modified version of such a theory, or by an idea or theory that was latent in the existing paradigm. Let us describe three examples of this kind of discovery.

Hertz, Roentgen and Bequerel

A series of serendipitous discoveries at the end of the nineteenth century heralded the approaching upheaval. The photoelectric effect, X-rays and radioactivity were discovered by serendipity and were later explained by theories which stemmed from the quantum idea, itself the product of serendipity.

The photoelectric effect was discovered in 1887 by Heinrich Hertz while he was conducting experiments related to the radio waves which he had discovered in 1886. He used a spark generator to produce the waves. In the course of these experiments he discovered by chance that the behavior of the spark gap was affected by the illumination of the electrodes. Other experiments following Hertz's observation showed that a piece of zinc illuminated by ultraviolet light became electrically charged. It was found that the effect is obtained for other metals and other wavelengths of light, provided the wavelength is below some threshold, irrespectively of the intensity of the light. The metal became charged because negatively charged electrons were ejected from it by the incident electromagnetic energy. It was further found that the speed of the ejected electrons was greater, the higher the frequency of the incident light. Increasing the intensity of the light beam only affected the number of electrons leaving the metal, which increased proportionally to the intensity. Below the threshold, however, no electron would be ejected at any light intensity.

After Planck's discovery of energy quantization Einstein was very quick to explain the photoelectric effect by conjecturing that light waves of frequency f consist of light-particles, photons, each of which carries an amount of energy $E=hf$. The intensity of the beam is proportional to the number of photons. Indeed, if the frequency of a light beam is less than some threshold f_0, no electron will be ejected, no matter how many photons there are in the beam, since none of them has enough energy to knock out an electron.

Roentgen's discovery in 1895 came as a by-product of a long research program triggered by Faraday. Faraday and his followers had investigated the phenomena which occur when an electric discharge is set up in partly evacuated glass tubes containing two electrodes. Advances in vacuum pump

technology led to the accumulation of new experimental data and to the conjecture that the luminescence which appears near the anode is produced by what were called "cathode rays". The research program culminated in 1897 with the results of J. J. Thomson's experiments showing that the cathode rays were negatively charged particles — electrons. The aim of the research program was to understand the nature of the cathode rays. However, before this aim was attained, X-rays were discovered by chance, as a by-product.

Roentgen inserted into the cathode-ray tube a metal plate which formed an angle with the path of the cathode-rays. At each discharge within the tube, Roentgen observed a bright illumination of a screen covered with a fluorescent salt situated outside the tube. It was evident that the cathode rays could not cause this glow since it had been previously proved that they cannot penetrate the glass walls. It turned out that the higher the vacuum in the tube, the more penetrating the new rays were.

The explanation of the X-ray phenomenon came later, with quantum theory and the atomic model. These rays are produced when high speed electrons (such as cathode rays) bombard a target atom and as a result one of the electrons in an inner shell of the atom is removed. The rearrangement of the electrons in the shells is accompanied by a decrease in energy and an emission of an X-ray photon.

The discovery of radioactivity in 1896 was even more accidental than the above two discoveries. Henri Bequerel knew about Roentgen's discovery and his aim was to find, as he says, "whether the property of emitting rays was not intimately bound up with phosphorescence". As phosphorescent substances he used uranium salts. He used a photographic plate wrapped with two sheets of thick black paper to protect the plate from sunlight. He placed a plate of the phosphorescent substance on the paper and exposed the whole thing to the sun. After developing the photographic plate, he saw the silhouette of the phosphorescent plate in black on the negative. One day, Bequerel tells us, when "the sun only showed itself intermittently, I kept my arrangements all prepared and put back the holders in the dark in the drawer of the case, and left in place the crusts of uranium salt. Since the sun did not show itself again for several days, I developed the photographic plates . . . expecting to find the images very feeble. The silhouettes appeared on the contrary with great intensity." After conducting further experiments he came to the conclusion that the phenomenon was not caused by radiation emitted by phosphorescence, and that the uranium salt itself emits radiation.

It was only after the famous experiments of the Curies that it was understood that radioactive elements such as uranium and radium disintegrate and change their chemical identity. Bequerel's discovery led, therefore, to the conclusion that chemical elements are not immutable and opened the way to the nuclear domain.

Let us now try to compare the theoretical explanations in these three cases to the above-listed three possible sources of variation enabling a species to meet new environmental conditions.

The understanding of the photoelectric effect is analogous to case (a) or (c), since it employed the idea of the quantum, which was invented for a different purpose and was not treated seriously until 1905. The understanding of X-rays is analogous to cases (a) and (b), since the phenomenon was explained by atomic physics, which had evolved from Planck's and Einstein's ideas and which was intended to explain other phenomena. Radioactivity was explained by employing ideas borrowed from chemistry, by using a heuristic of the Meyersonian kind for constructing matter–theories [case (a)].

Thus, a discovery of a novel phenomenon may foster theoretical advance, just as changing environmental conditions may foster evolutionary progress. In each of the above examples the resulting theoretical advance was serendipitous, since the new phenomenon was exposed following an experimental activity guided by an established theory or by an entrenched conception, whereas the end result was the adoption of another theory or conception which superseded the original one. In other words, the original research employed a guiding theory or conception to solve a given problem, whereas the end result was its rejection or a radical change imposed on it. Hence the epistemological significance of such a discovery is in triggering the process of replacing an entrenched conception or theory. This sort of serendipitous discovery, like blind discovery of new explanatory ideas and solutions of problems, serves therefore as a means of transcending an entrenched framework of knowledge. In addition, as the example of the discovery of penicillin indicates, such a process can be viewed as a serendipitous discovery of a solution of a technological problem. The discovery of penicillin solved an acute medical problem. The discovery of X-rays and radioactivity solved experimental problems within physics itself by providing new methods for probing the structure of matter. The discovery of an anomalous phenomenon which is unexpected in view of the entrenched background knowledge must, indeed, be serendipitous.

We would expect that discovery by serendipity of new phenomena will be more frequent in sciences which do not yet have a fully developed theoretical system to guide research. Indeed, this is very common in certain areas of the medical sciences, such as drug research; our above example of the discovery of penicillin by Fleming is repeated again and again in this field. It has also typically occurred, as we saw above, in fluid stages in the evolution of physics: other classical examples are: Galvani's discovery leading to the electric battery, Brown's discovery of molecular motion (two cases of interdisciplinary serendipity), and Oersted's discovery of the nature of the connection between electricity and magnetism. Other examples are described in Cannon (1968) and in Shapiro (1986).

References

Amundsen, R. (forthcoming), 'The Traits and Tribulations of Selectionist Explanations', in: *Issues in Evolutionary Epistemology* (State University of New York Press).

Campbell, D. T. (1974a), 'Unjustified Variation and Selective Retention in Scientific Discovery', in: *Studies in the Philosophy of Biology*, F. J. Ayala and T. Dobzhansky (eds) (London: Macmillan), pp. 139–161.

Campbell, D. T. (1974b), 'Evolutionary Epistemology', in: *The Philosophy of Karl Popper*, Vol. 1, P. A. Schilpp (ed) (La Salle: Open Court), pp. 413–463.

Cannon W. (1961), 'Gains From Serendipity', in: *The Way of an Investigator* (New York: Hafner).

Dobzhansky, T., Ayala, F. J., Stebbing, G. L. and Valentine, J. W. (1977), *Evolution* (San Francisco: W. H. Freeman).

Goldstone, J. (1961), 'Field Theories with Superconductor Solutions', *Nuovo Cimento* **19**, 155.

Higgs, P. W. (1964), 'Broken Symmetries, Massless Particles and Gauge Fields', *Physical Review Letters* **13**, 508.

Kantorovich, A. (1979), 'Towards a Dynamic Methodology of Science', *Erkenntnis* **14**, 251–273.

Kantorovich, A. (1988), 'Philosophy of Science: From Justification to Explanation', *The British Journal for the Philosophy of Science* **39**, 469–494.

Klein, M. J. (1966) 'Thermodynamics and Quanta in Planck's Work', *Physics Today*, November.

Koestler, A. (1964) *The Sleepwalkers* (Pelican: Harmondsworth, U.K.).

Lakatos, I. (1970), 'Falsification and the Methodology of Scientific Research Programmes', in: *Criticism and the Growth of Knowledge*, I. Lakatos and A. Musgrave (eds) (Cambridge: Cambridge University Press), pp. 91–196.

Lewis, W. S. (ed) (1960), *Horace Walpole's Correspondence*, Vol 20/IV, (New Haven: Yale University Press), p. 407.

Meyerson, E. (1908), *Identité et Réalité* (Paris).

Nambu, Y. and Jona-Lasinio, G. (1961), 'Dynamical Model of Elementary Particles based on an Analogy with Superconductivity', *Physical Review* **122**, 345 and **124**, 246.

Nambu, Y. (1976), 'The Confinement of Quarks', *Scientific American* **235**, 5–48.

Ne'eman, Y. (1963), 'Baryon Charge and R-inversion in the Octet Model', *Nuovo Cimento* **27**, 1–5.

Ne'eman, Y. (1966), 'Hadron Matrix Mechanics', in: *Symmetry Principles at High Energy*, Vol. 3, A. Perlmutter *et al.* (eds) (San Francisco: W. H. Freeman), pp. 137–149.

Ne'eman, Y. (1980), 'Science as Evolution and Transcendence', *Acta Scientifica Venezolana (Ensayo)* **31**, 1–3.

Ne'eman, Y. (1987), 'Hadron Symmetry, Classification and Compositeness', in: *Symmetries in Physics 1600–1980*, M. G. Doncel *et al.* (eds) (Universitat Aut. de Barcelona Servei de Publicacions), pp. 499–540.

Ne'eman, Y. (1988), 'The Classification and Structure of Hadrons', in: *From Pions to Quarks*, M. Dresden *et al.* (eds) (Cambridge: Cambridge University Press).

Pickering, A. (1984), *Constructing Quarks* (Cambridge: Cambridge University Press).

Scherk, J. and Schwarz, J. H. (1974), 'Dual Models for Non-hadrons', *Nuclear Physics* **B81**, 118–144.

Schwarz, J. H. (ed) (1985), *Superstrings* (Singapore: World Scientific).

Shapiro, G. (1986), *A Skeleton in the Darkroom — Stories of Serendipity in Science* (San Francisco: Harper & Row).

Yoneya, T. (1974), 'Connection of Dual Models to Electrodynamics and Gravidynamics', *Progress in Theoretical Physics* **51**, 1907–1920.